

AUSTIN BECKER, DAVID NEWELL, MARTIN FISCHER AND BEN SCHWEGLER



WILL PORTS BECOME FORTS? CLIMATE CHANGE IMPACTS, OPPORTUNITIES AND CHALLENGES

ABSTRACT

While many studies characterise the causes of sea-level rise, attempt to measure and predict its rate of change, the focus on planning for the response that would be required to protect coastal communities in the event that sea-level rise does occur on a significant scale has been comparatively small. Understanding that many ports could face similar challenges at roughly the same time and the constraints for such a response caused by this has also been given little attention. This article presents the Stanford University Policy and Engineering Responses to Sea Level Rise (SUPERSLR) project that has examined various solutions featuring “hard” (e.g., seawalls) and “soft” (e.g., managed retreat) measures that would be suitable for the different conditions found at coastal and port cities worldwide. Three particularly important areas of investigation are reviewed here: The quantification of resources, time, and cost required to implement the “hard” solution of constructing coastal defenses; A survey of the world’s port authorities; and barriers to decision making in seaport systems. Parts of this article have been adopted from Becker, A., Fischer, M., Inoue, S., Schwegler, B. (2011, in press), ‘Climate change impacts on seaports: A global survey of perceptions and plans’, *Journal of Climatic Change*.

INTRODUCTION

How can seaports prepare for sea-level rise? Most approaches would likely incorporate some form of known engineering solutions. However, many ports are at today’s sea level and the 0.6 to 2 metres of rise projected for the end of the century could present significant challenges. While many studies characterise the causes of sea level rise and attempt to measure and predict its rate of change (Vermeer and Rahmstorf 2009), comparatively little focus has been given to planning for the response that would be required to protect coastal communities in the event that sea level rise does occur on a significant scale (Brooks et al. 2006) and to understanding the constraints for such a response given that many ports could face similar challenges at roughly the same time.

Could engineered protection be implemented on a global scale should that become necessary? What would the future solutions

Above: As 80% of the world’s freight moves by ship, ports and harbours serve a critical and central role in the global economy. Climate impacts on maritime infrastructure resulting in sea-level rise are therefore an area of great concern and one in which little work has been completed.

to protect seaports against sea level rise look like? The Stanford University Policy and Engineering Responses to Sea Level Rise (SUPERSLR) project has examined various solutions featuring “hard” (e.g., seawalls) and “soft” (e.g., managed retreat) measures that would be suitable for the different conditions found at coastal and port cities worldwide. Three particularly important areas of investigation are reviewed here:

- 1 *The quantification of resources, time, and cost required to implement the “hard” solution of constructing coastal defenses.* By aggregating on a global scale the maximum industry capacity required for the simultaneous construction of protection structures around the globe has been estimated. Based on foreseeable growth trends in the construction industry, preliminary results show that current capacity would be exceeded. Indicators of the kind of industry strain ahead include the challenges faced by the U.S. construction industry in responding to the ravage of Hurricane Katrina (Kates et al. 2006).
- 2 *A survey of the world’s port authorities.* Conducted in cooperation with the International Association of Ports and Harbors (IAPH) and the American Association of Port Authorities (AAPA), a survey found that the majority of ports are concerned

about the impacts of sea-level rise, but not are yet implementing adaptation strategies.

3 Barriers to decision making in seaport systems. Through case studies, the research team is working with local decision makers to identify site-specific strategies for climate change adaptation, the path to implementation, and an understanding of barriers that the decision-making system faces to carry out large-scale changes such as those needed for building coastal resilience.

Climate change motivation

Amongst the many predicted scenarios likely to result from climate change is an increase in the mean sea level (MSL) of between 0.6 and 2 metres on a planetary scale by 2100 (Intergovernmental Panel on Climate Change (IPCC) 2007; Rahmstorf 2010) and an intensification of tropical cyclones. Although the sea-level changes and storm effects differ depending on the location in question (IPCC 2007; NRC 2010), it is clear that at some point additional protection in the form of dikes, levees, sea walls, fill, and such, will be required to protect ports, harbours, and other coastal developments where the cost, resource requirements, and practicality of relocation or port elevation from the current grade is believed to outweigh the constructed alternative (Nicholls 2007).

Given the expected life span of port infrastructure it seems prudent to understand the

potential impacts of MSL and the related effects on port infrastructure and operation and to identify the most critical constraints for a response.

Why ports?

Using seaports as a unit of study sets clear boundaries for analysis, since ports have fixed locations and simple measures for determining economic value in the form of shipping volume. Ports also serve as an example of infrastructure that explicitly relies on coastal locations. Unlike other coastal uses, ports must be situated in areas that are vulnerable to the impacts of climate change. As 80% of the world's freight moves by ship, ports serve a critical and central role in the global economy (International Maritime Organization (IMO) 2008). National and international organisations have identified that climate impacts on maritime infrastructure is an area of great concern in which little work has been completed (Moser 2008; UNCTAD 2008; USCOP 2004; USEPA 2008).

Ports require special treatment because of their economic importance as essential links in supply chains, their locations in the heart of sensitive estuarine environments, their reliance on waterfront locations, and the significant existing infrastructure that links them to inland transportation networks. Unlike other coastal uses like residential or retail, ports cannot be relocated to safer locations. Lacking

practical options for retreat, engineered solutions such as armouring must be considered seriously if ports are to continue operating as they have in recent history.

A recent United States Environmental Protection Agency (USEPA 2008) report on climate impacts on seaports states, "most [U.S.] ports do not appear to be thinking about, let alone actively preparing to address, the effects of climate change" (USEPA 2008). Results of a survey conducted by the SUPERSLR team confirms this propensity on a global scale (Becker et al., in review). Policy makers, insurers, the international community, and the ports themselves will all play a role in preparations for sea-level rise.

For the past three years, the Stanford teaching team has brought undergraduate and graduate students together in SUPERSLR courses to study various aspects of these issues. Experts from a wide variety of institutions discuss engineering, science, industry and policy perspectives on climate change adaptation and the coastal built environment. Over 50 independent studies have been conducted, each exploring a particular area, including specific port case studies, environmental impacts, and international policy frameworks. Students choose their own projects that fit into various themes selected by the teaching staff to contribute to the overall project. This degree of freedom gives students the opportunity to explore one of their interest areas in a unique class setting.

CREDIBLE MINIMUM-CRITERIA COASTAL PROTECTION DESIGN FRAMEWORK

In order to study the "hard" protection strategy for ports around the world, a traditional engineering study of each port would have required an inordinate amount of time to complete a site-specific design. To counter this problem, researchers at Stanford developed a minimum-criteria design frameworks for various hard structures to get an estimate of the amount of materials required without the time required to study each port in extensive detail. The keystone for this part of the project is a system for handling geographic data and running computer models inside Google Earth, called "Sebastian."



Figure 1. Sebastian GeoData results for Marseilles, France displayed in Google Earth.



AUSTIN BECKER

is a Ph.D. candidate in the Emmett Inter-disciplinary Program in Environment and Resources at Stanford University. He is researching the risks and vulnerabilities posed by climate change to seaports and dependent socio-political systems. Prior to Stanford, he worked as a coastal manager in Rhode Island, focussing on working-waterfront and port land-use policies. He earned a Masters of Marine Affairs (2005) and Masters of Environmental Science and Management (2006) from the University of Rhode Island. He also holds a 500-Ton U.S. Coast Guard captain's license for ocean-going vessels.



DAVID NEWELL

a 4th year engineering student at Stanford University, majoring in Management Science and Engineering, has worked with several organisations to solve business problems using technological solutions, such as simulation models and optimisation methods. He has worked with Stanford's SUPERSLR project for 3 1/2 years, presenting this research in Argentina, Australia, Germany and the Netherlands.



MARTIN FISCHER

is Professor of Civil and Environmental Engineering at Stanford and also serves as Director of the Center for Integrated Facility Engineering (CIFE), an industry-sponsored, academic research centre. He is known as a leader in developing virtual 4D modelling (time plus 3D) methods to improve project planning and facility life-cycle performance, increase project teams' productivity and further the sustainability of the built environment. He holds a PhD in Civil and Environmental Engineering and an MS in Industrial Engineering from Stanford and a Diploma in Civil Engineering from the Swiss Federal Institute of Technology, Lausanne.



BEN SCHWEGLER

is a Ph.D. and Vice President and Chief Scientist of Walt Disney Imagineering R&D, responsible for Imagineering's Sustainable Design and Engineering group; a multidisciplinary organisation of engineers, architects, scientists and other design professionals chartered to understand the interaction of the built and natural environments. He is also a consulting professor at Stanford University and serves on the Advisory Boards of the Precourt Institute for Energy Efficiency at Stanford and the Jet Propulsion Laboratory's Technical Divisions.

Resource Production

The charts below show the differences in cement, gravel, and sand production throughout the world.

Cement

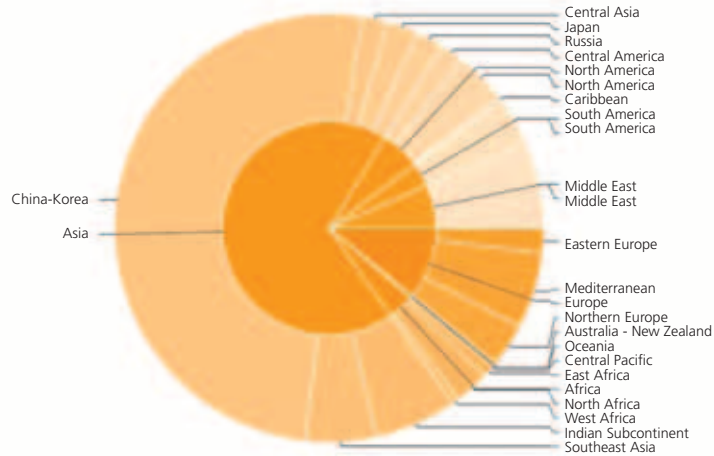


Figure 2. Data tables and graphs of calculated materials.

Sebastian GeoData System

The credible minimum-criteria design framework provides a sufficient level of credibility for an order-of-magnitude study of the amount of materials required to protect seaports against sea-level rise using a hard structure. The most complete design to date is a dike structure that is currently used in the Sebastian GeoData System. This system generates material requirements to allow for global materials demand data analysis. While using this particular dike design for any particular port is not advocated per se, it is a solution that could feasibly work at any port and thus provides useful outputs for global estimations. Since this project only seeks to begin the planning process for responses to sea-level rise, it is not logical to invest a significant amount of time in a full bespoke engineering study for every individual port where a conceptual design is sufficient to answer the questions researchers have posed.

The Sebastian GeoData System follows a simple framework to model a hard protection structure for any port worldwide. Using Google Earth's built-in drawing tools, the protection area is specified by the user along with the start and end areas for the dike. Then, the computer model uses topography and bathymetry data to build a dike pathway that minimises the length and depth, optimising the amount of materials required.

The result is then displayed in Google Earth (as shown in Figure 1 for Marseilles, France).

Sebastian aggregates these calculated materials requirements for every port analysed and displays summary information as data tables and graphs inside of Google Earth (as shown in Figure 2). Through these steps, a series of ports may be analysed by users from around the world and the results promptly compiled to inform decision makers and other stakeholders. The Sebastian tool is designed to be flexible so that it may grow to incorporate future solutions as they are developed.

Which ports?

Stanford researchers selected the 180 economically most important ports based on various factors, including ports that serve a population of greater than 1 million or are in the top 50 in terms of shipping volume by tonnage or containers, which captures approximately 2/3 of all shipping traffic. These important ports provide a good subset for study, since it would be unrealistic and extremely time-intensive to investigate all 3,000-4,000 ports worldwide.

Global construction industry capacity

To understand the particular limiting factors in responding to sea-level rise, it is necessary to determine the current availability resources. The SUPERSLR Research Database contains



Figure 3. As of November 2010, Stanford researchers had analyzed 165 of the prescribed set of 180 ports here.

these data and when combined with the output from Sebastian port models, the limiting factors are revealed. The research methodology for understanding the global construction industry’s capacity, as well as some of the preliminary results is described in the following sections.

Construction materials

The primary construction materials currently used in coastal defenses are concrete and steel. Thus, it is important to investigate the known supplies and regional accessibility of cement, coarse aggregate, and fine aggregate. Various public repositories contain data for the estimate of global material supply availability for common construction materials (USGS 2010). Preliminary results indicate that the global capacity for producing these materials is insufficient for constructing the protective structures around each of the world’s top economic ports in less than 50-60 years. Although fill is also a critical component of most protection structures, it would most likely be available locally and procured through dredging, and is thus not expected to be a limiting factor.

Coastal engineers

Researchers are in the initial stages of determining how many coastal engineers are

presently available globally. Preliminary estimates for the United States indicate that fewer than 5,000 coastal engineers are employed by various firms across the country, and no more than 10,000 worldwide (Greenfield 2009). These data point to a shortage of coastal engineers in the future, particularly if this dike concept were to be applied at many ports worldwide.

Costs and time to complete

Using data from RS Means construction costs and labour guides, researchers estimated both the time to complete the construction of each port’s defence design as modelled using Sebastian and the costs associated with this construction. While most of these figures from RS Means are not specified for coastal engineering projects, they are fairly accurate when compared with past dike construction projects. Preliminary findings suggest that, on average, each port would require 520,000 work-hours (about 12.5 years using a 20-employee team) to construct a modelled design solution to protect against 2 metres of SLR, and each defense would cost over US\$1.2 billion (Reed Construction Data Inc. 2008).

Dredging

Coastal defense structures generally require seabed preparation before construction may

begin. Dredges perform this operation. Additionally, in the case of our dike design, dredged material with the appropriate properties could be used for the fill, which makes up the majority of the structure. This research considered only the dredging required to prepare the sea floor for the structure’s foundation. Across all 180 seaports, the average dredging volume required is about 5.9 million cubic metres for a total volume of 935 million cubic metres, or approximately three times the annual U.S. waterways dredging (Verna and Poynton 2004).

In the construction of the Oosterschelde storm-surge barrier in the Netherlands, a minimum of five dedicated ships were built specifically to meet project requirements (Deltawerken 2011). For the Port of Rotterdam’s new Maasvlakte 2, between 3 and 10 dredges are in operation at any time (Port of Rotterdam 2010).

Although dredging jobs are described by the type of material dredged, this research considered sand, for which only trailing suction hopper dredges and cutter suction dredges would be appropriate. There exist 492 and 405 of each of these dredges, respectively (Oilfield Publications Limited 2010). If these dredges could move 30,000 and 50,000 cubic metres of sand per day, respectively, and work 80% of the year, the total amount of sand that could be moved in one year is 10.2 billion cubic metres. In other words, the increased demand generated by this global project would be about 9% over current annual capacity, not a dramatic change, but definitely an increase in available work.

Results

As of November 2010, Stanford researchers had analysed 168 of the prescribed set of 180 ports, shown in Figure 3. Extrapolating these data points to all 4,235 ports from 195 countries in the “World Port Source” database, (www.worldportsource.com), the estimated demands for cement, sand, and gravel are shown in Table I. The capacity and demand requirements under this scenario reveal a need for 1.4 years of current cement production and over 6 years of sand and gravel production.

While it is certainly possible to procure this amount of materials, it would strain the

Table I. Resource production and demand requirements for the global market. Production and demand in billion metric tons. (Data current as of January 21, 2011).

Resource	Yearly Production	Estimated Demand	Est. Years of Production
Cement	2.93	4.14	1.41
Sand	1.52	10.4	6.84
Gravel	2.71	16.4	6.05

industry, and new supplies of sand and gravel would need to be developed if this project were to proceed. Some research remains, but it is certain that this type of response would greatly affect the coastal construction industry as the demand for equipment and materials grows substantially. Preparing for sea-level rise could bring dramatic changes to how the coastal construction industry conducts its business.

GLOBAL SURVEY OF PORT AUTHORITIES

Information in this section has been adopted from Becker, A., Fischer, M., Inoue, S., Schwegler, B. (2011 in press), "Climate change impacts on seaports: A global survey of perceptions and plans", *Journal of Climatic Change*. To assess the current state of knowledge, researchers distributed surveys to 342 port authorities from around the world to ascertain how administrators feel climate change might impact their operations, what sea-level change would create operational problems, and how they plan to adapt to new environmental conditions.

This research aimed to discover what policies, if any, ports already have in place to address adaptation issues. Ninety-three port directors, engineers, environmental managers, and planners representing 89 ports responded to the survey giving a broad picture of the current state of the world's ports with respect to climate change. 63% of respondents reported that they had at least one policy that specifically addressed potential climate change effects or that they discussed adaptation in staff meetings. The survey responses showed few significant differences between ports of different sizes or regions, but indicated that US Gulf Coast ports appeared to be the most prepared. This higher level of preparedness probably results from the large number of recent storms in the Gulf.

The design lifetime of port infrastructure is 30-50 years, but often infrastructure like roads, bridges, piers, and rail yards will last much longer (UNCTAD 1985). Much infrastructure built today will still stand as climatic conditions change over the course of the century. As these projects compete for resources with other business or community needs, long-range implications of today's

Port Planning Horizons

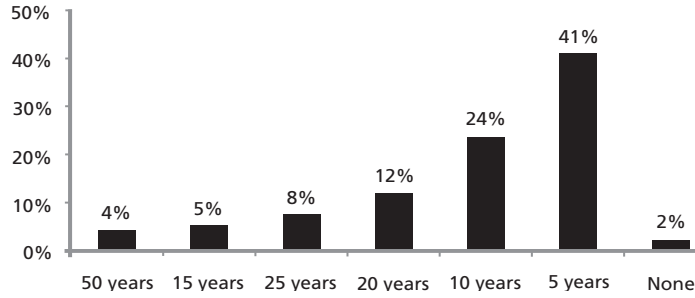


Figure 4. Ports' planning horizons in years.

choices often have less of a sense of urgency than more immediate priorities. Survey results indicate that capital planning cycles at ports are typically 5 to 10 years. This mismatch between planning cycles and infrastructure lifetimes may be at the root of many structural organisational difficulties in addressing this complex issue.

To establish a general sense of how ports plan for future expansion and development of their infrastructure and cargo-handling facilities, the survey asked about planning horizons and specific plans for future projects. Though, of course, there are various "planning horizons" for different types of projects and outcomes, the survey asked specifically about plans for capital improvements, expansion, and maintenance.

Most ports planned on a 5-10 year horizon (Figure 4) and the majority were planning for some level of expansion of their facilities.

Those with planned projects indicated that most plans were for more terminals and berths or for land acquisition (Figure 5). Only a small percentage of ports have upcoming projects like new breakwaters or storm barriers that would increase their defenses against flooding and wave damage.

The specific risks associated with climate change are no different in nature than historic risks. Most ports face some amount of wind, wave, and flooding risk already and have already built infrastructure to protect port operations. However, the degree of risk will likely change as storms become more intense and sea levels rise. In an open-ended question which asked respondents to list the top three impacts climate change might have on their port's operations, "sea level rise" was listed by 27 respondents. Other impacts of note included storms, flooding, shifts in markets, wave and wind impacts, environmental regulations and dredging.

Design standards and new construction plans in the next 10 years*

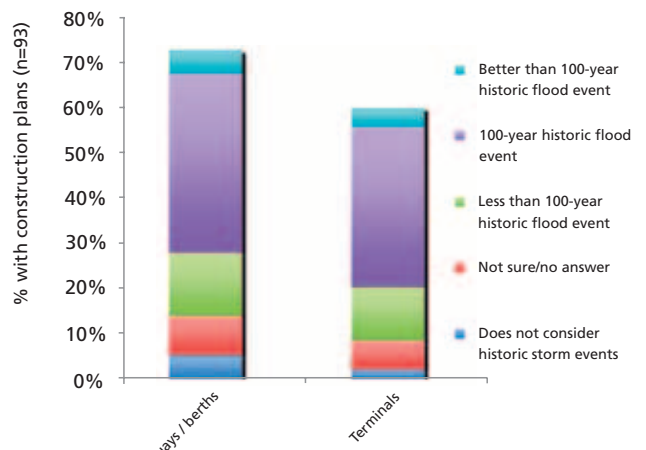


Figure 5. Design standards and construction plans for all respondents.

* 16% of those planning new infrastructure also plan on building new storm protections

Since most respondents represent ports that are in coastal areas prone to storm events, they will likely design new structures with a particular extreme-event threshold in mind.

Survey results indicate that most ports in Europe, North America, and Oceania followed a 100-year return period planning standard. This means that a structure will be designed to withstand a storm that has a one-percent chance of occurring in any given year. However, 30% of Asian ports and 43% of ports in Central/South America planned with the most recent storm in mind. A few ports planned for a much longer return periods, with one port answering that they planned for a 1-in-1000 year storm event. It should be noted that storm forces are different in different areas of the world. For example, a 1-in-1000 year event in the Netherlands has roughly the same forces as a 1-in-100 year event in New Orleans. Thus, there is no universal storm period standard for designing structures to withstand storm events and it may not be feasible for all areas to implement such a high standard as the 1-in-1000 year event (Peter Wijsman, personal communication, May 15, 2009).

To get a better sense of what policies had already been actually implemented at the port, respondents were asked to identify which of seven policies they had already implemented (Figure 7).

Many respondents either did not know or said they were not addressing these issues at this time (47%). When asked about protective measures currently in place at the port, only 22% of respondents were found to have a storm plan in place and only 23% carried specific storm insurance. There was no correlation between a port's location relative to the storm belt and its plans to develop new

protective structures in the next 10 years, nor between insurance coverage and protection plans.

A rough scoring system assigned a point for each answer selected from the list of choices in Figure 6 and tallied the points for each port. The highest "score" was a five, meaning that the respondent indicated that the port had five of the potential seven options in place. The lowest score was a zero and the mean for all ports was 1.18 (1.24 standard deviation). Although this scoring system is not perfect, it enables some rough comparisons between ports. Ports were compared by size, World Bank status, location, and other categorisations. Most comparisons showed little or no significant difference. However, ports that carried standard insurance averaged 1.5 points, a bit higher than those that were self-insured (1.17), carried co-op insurance (0.7), or carried no insurance at all (1.3). Geographically, ports located in high-income nations averaged 1.3, 1.0 in upper and middle-upper income averaged 1.0, 0.75 in low income (0.75), and 0.5 in lower-middle income nations.

This scoring system offers insights into how ports compare relative to current climate preparation. In most cases, scores were within a standard deviation (SD = 1.24) of each other. The finding that high-income nations have more policies in place could be an initial step in discovering which ports have already thought about adaption problems and could provide models for those wishing to develop similar programmes.

Additionally, further investigation should be directed at the difference found between ports with standard insurance versus ports with other types of insurance in place.

Perhaps, for example, insurance companies are requiring ports to implement new policies. The highest scoring category was Gulf Coast Ports (with an average score of 2). Gulf Coast Ports have faced numerous hurricanes in the past decade. Land subsidence is also considerably greater on the Gulf Coast.

Overall, survey results show that the world port community is very concerned with impacts of climate change, but generally is not taking proactive action to adapt. This situation must be resolved if decisions are to be made that will protect both the port infrastructure itself and the economic systems that depend on a resilient and efficient maritime industry.

IMPLEMENTING ADAPTATION STRATEGIES: A CASE-STUDY APPROACH TO INTEGRATED DECISION MAKING

Continuing research at Stanford uses seaports as a case study to develop a better understanding of how institutional systems define resilience, how they can change in order to adapt to climate change, and what stands in the way of implementing adaptation strategies. A comparative case study of three seaports addresses the primary question: *What are the decision-making barriers to improving storm resilience?*

Data collected in interviews and focus groups with local decision makers will be used to quantify, compare, and contrast individual and system-wide constructs of resilience-building within the port systems and ultimately define the primary impediments to change. Climate change adaptation requires a holistic and sustainability-based perspective, as climate extremes place new demands on both human-built infrastructure and the natural environment.

This research will analyse the port as a system of decision-making actors and develop the concept of the "port decision-making system" as an example of a knowledge system that centres around primarily economic, but also social and environmental, goals for a well-functioning port. A testable framework will describe the impacts of extreme events on port systems in general and the options and tools at the knowledge systems' disposal for enhancing resiliency. This work addresses the need for

Climate adaptation policies in place

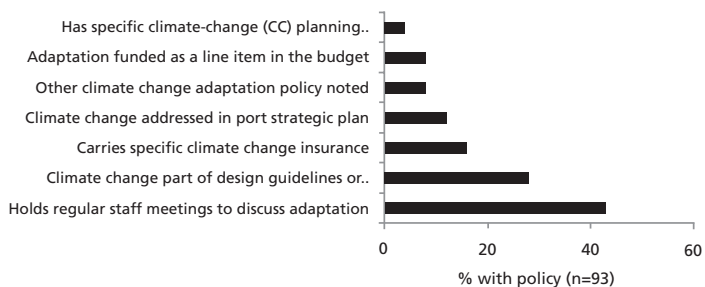


Figure 6. Climate policies in place.

research into impacts of climate change adaptation and specifically issues facing coastal infrastructure (Clark 2000; USEPA 2008).

CONCLUSIONS

Responding to sea-level rise and intensification of storm events requires a suite of strategies and an implementation schedule that decision makers can agree upon. By looking at the feasibility of engineered solutions, the perceptions and plans of ports themselves, and the decision-making system as a whole, the research team at Stanford University is developing approaches necessary to meet the new demands of a changing environment. While current operational challenges may make it difficult for individual companies to devote resources to this long-term issues, the implications of climate change impacts on many industries, including dredging, will be quite profound as evident from these preliminary results.

Interested parties are invited to work with Stanford and industry associations may wish to take the helm at the forefront of aggregating information that informs this issue and connects parties to collaborate and work toward solutions. The Stanford researchers' current body of work and ongoing projects, including the aforementioned global survey of port administrators, may be found through their website: www.seaports2100.org.

REFERENCES

- Becker, A., Fischer, M., Inoue, S., Schwegler, B. (2011, in press), "Climate change impacts on seaports: A global survey of perceptions and plans", *Journal of Climatic Change*.
- Brooks, N., Hall, J., and Nicholls, R.J. (2006), *Sea level rise: coastal impacts and responses*.
- Clark, W., Jaeger, J., Corell, R., Kasperson, R., McCarthy, J., Cash, D., Cohen, S., Desanker, P., Dickson, N., Epstein, P., Guston, D., Hall, M., Jaeger, C., Janetos, A., Leary, N., Levy, M., Luers, A., MacCracken, M., Melillo, J., Moss, R., Nigg, J., Parry, M., Parson, E., Ribot, J., Schellhuber, H.J., Schrag, D., Seielstad, G., Shea, E., Vogel, C., Wilbanks, T. (2000), "Assessing vulnerability to global environmental risks. Report of the Workshop on Vulnerability to Global Environmental Change: Challenges for Research, Assessment and Decision Making", *Research and Assessment Systems for Sustainability Program Discussion Paper 2000-12*. Environment and Natural Resources Program, Belfer Center for Science and International Affairs (BCSIA), Kennedy School of Government, Harvard University, Cambridge, MA.
- Deltawerken. "Welcome to Deltawerken". <http://www.deltawerken.com/>, accessed 01/15/2011.
- Goda, Y. (2000). *Random seas and design of maritime structures*. World Scientific Pub Co Inc.
- Greenfield, Nick (2009). "World Estimates and Explanations for Coastal Engineers". Stanford CEE 129 Student Reports (unpublished).
- Hammel, Leigh (2009), 'Global Ship Capacity: Are there enough ships to protect our ports from sea level rise?', Stanford CEE 229 Student Reports (unpublished).
- Moser, Hans, Hawkes, Peter J., Arntsen, Øivind A., Gaufres, Pierre, Mai, France Stephan, Pauli, Gernot, and White, Kathleen D. (2008). *Envicom – Task Group 3: Waterborne transport, ports and waterways: A review of climate change drivers, impacts, responses and mitigation*. International Navigation Association (PIANC).
- Intergovernmental Panel on Climate Change (IPCC) (2007). "Climate Change 2007: Impacts, Adaptation and Vulnerability", in M.L. Parry, Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (ed.), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK.
- International Maritime Organization (IMO). "International Shipping and World Trade Facts and Figures". <http://www.imo.org/KnowledgeCentre/ShippingFacts-AndNews/TheRoleandImportanceofInternational-Shipping/Pages/TheRoleandImportanceOfInternational-Shipping.aspx>, accessed 02/10/2009.
- Kates, RW, et al. (2006), 'Reconstruction of New Orleans after Hurricane Katrina: a research perspective', *Proceedings of the National Academy of Sciences*, 103 (40), 14653. National Academies Press, Washington, DC.
- Nicholls, R., S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfee-Morlot, J. Chateau, and R. Muir-Wood (2007), 'Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates', *OECD Environment Working Paper 1*, ENV/WKP(2007)1. OECD, Paris, France.
- Oilfield Publications Limited (2011). *Dredging Vessels of the World*. <http://www.sandandgravel.com/dredging-vessels/welcome2.html>, accessed 01-15-2011.
- Port of Rotterdam (2011), "Construction of Maasvlakte 2 running like clockwork" <http://www.portofrotterdam.com/en/News/pressreleases-news/Pages/Constructionof-Maasvlakte2runninglikeclockwork.aspx>, accessed 1-15-2011.
- Rahmstorf, S (2010). "A new view on sea level rise". *Nature Reports Climate Change*, 44-45.
- Reed Construction Data Inc.(2008). "RSMean Cost Data", in R.S. Means Company (ed.). *United Nations Conference on Trade and Development (2008), "Maritime transport and the climate change challenge"*, Note by the UNCTAD secretariat. United Nations, Geneva, Switzerland.
- United Nations Conference on Trade and Development (UNCTAD) (1985). "Port development: A handbook for planners in developing countries". United Nations Conference on Trade and Development, New York.
- United States Commission on Ocean Policy (USCOP) (2004). "An Ocean Blueprint for the 21st Century. Final Report". Washington, DC: United States Commission on Ocean Policy.
- United States Environmental Protection Agency (USEPA) (2008). "Planning for Climate Change Impacts at U.S. Ports. White Paper prepared by ICF International for the USEPA".
- United States Geological Survey (USGS) (2011), "Mineral Statistics and Information from the USGS", <http://minerals.usgs.gov/minerals>, accessed 01/15/2011.
- Vermeer, M. and Rahmstorf, S. (2009). "Global sea level linked to global temperature", *Proceedings of the National Academy of Sciences*, 106 (51), 21527.
- Verna, T.M. and Pointon, M.R. (2004). "US Army Corps of Engineers Dredging of Channels and Waterways". *American Society of Civil Engineers*.
- Water, Mark. *World Port Source Database*. <http://www.worldportsource.com>. Accessed 09/15/2010.
- Wijsman, P., Program Manager at ARCADIS US, Inc., Telephone Interview. May 15, 2009.